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ADP013284

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ADP013147 thru ADP013308

9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Dynamic susceptibility of 1D conductors: the short-range electron correlation effect

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Abstract. The dynamic density response and susceptibility of interacting electrons in 1D conductors is investigated taking into account the electron correlations reflecting the short-range order in a Luttinger liquid. We have shown that a narrow band of strong absorption appears in the dissipative susceptibility spectrum near to the wave vector $2k_F$ due to the short-range correlations, in addition to the commonly known δ-peak coming from the long-wave fluctuations. The adsorption band shape depends on the electron-electron interaction potential. This band is found to contribute dominantly to the dissipative conductance determined via the power absorbed in 1D conductor under local excitation.

Introduction

The electron-electron interaction in 1D conductors gives rise to the strongly correlated Luttinger liquid [1]. In this state the correlation function decreases slowly with distance showing the existence of short-range order. The electron density excitations are characterized by the existence of two components. One of them is a long-wavelength (LW) fluctuation coming from compression and extention of the Luttinger liquid. It caused mainly by the forward scattering processes. The other component arises due to backward scattering of electrons. It is represents the electron density oscillations on the scale of inter-electron distance. This component is similar to the charge-density waves (CDW) in Pierls conductors. The LW density component, as well as its contribution to transport properties, is well investigated in the literature. The CDW component was explored only in the connection with the pinning of a Luttinger liquid by impurities. It is obvious, that since short-range electron correlations contribute to the density, they must also contribute to transport even if there is no impurity.

In the present paper we investigate the dynamic density response and susceptibility of interacting electrons in 1D conductors taking into account the CDW component of the electron density. We have found that the short-range electron correlations produce a narrow band of strong absorption near to the wave vector $2k_F$, in addition to the commonly known δ-peak coming from the LW fluctuations. The band shape depends strongly on the electron-electron interaction potential. We have considered a scheme of experiment where the 1D conductor is subjected to the local external potential and the dissipated power is measured. Our calculations show that the contribution of CDWs to the absorbed power dominates over that of the LW density in the low-frequency regime.

1. The electron density

The collective motion of electrons is described by the bosonic phase $\Phi(x, t)$ which is connected with the electron density $\rho(x, t)$. The standard expression, which relates the

CDW density to Φ, was recently shown [2] to contradict to the requirement of the total particle number conservation. The correct expression of the density operator via Φ was proposed in Ref. [2]

$$\rho(x,t) = -\frac{1}{\pi}\partial_x\left[\Phi - \frac{1}{2}\sin(2k_F x - 2\Phi)\right], \tag{1}$$

where k_F is the Fermi wave vector. The first term describes the LW excitations that are smooth on the k_F scale. The second (oscillating) term relates to CDWs. The oscillations reflect the real physical picture of the excitations in a Luttinger liquid. In addition to the elastic waves, which are due to the LW density, the electrons are undergone the back scattering by neighboring particles. The interferences of the right- and left-moving electrons results in the density oscillations with the characteristic scale of $2k_F$. The oscillating density is also disturbed by an external potential and corresponding fluctuations propagate along the conductor contributing to the susceptibility, the current response and dissipated energy.

2. The dynamic susceptibility

The density response function $\chi(x,t)$ and the dynamic susceptibility are calculated using the bosonization technique and the Kubo formula.

The response function $\chi_1(x,t)$, which is due to LW density, represents the compression and extension waves in the Luttinger liquid moving from the excitation point. These waves are of the simplest form in the case of short-range interaction. They propagate with a constant velocity v renormalized by the interaction ($v = v_F/g$, with g being the interaction parameter). In the Coulomb interaction case, the charge waves propagate with dispersion. The velocity increases with the time as $(\ln t)^{1/2}$ which results in smoothing of the fronts and in the density oscillations.

The susceptibility $\chi_1(q,\omega)$ caused by the LW density has the pole at $\omega = qv(q)$ (with q being the wave vector, ω the frequency). It corresponds to the well-known plasmon pole.

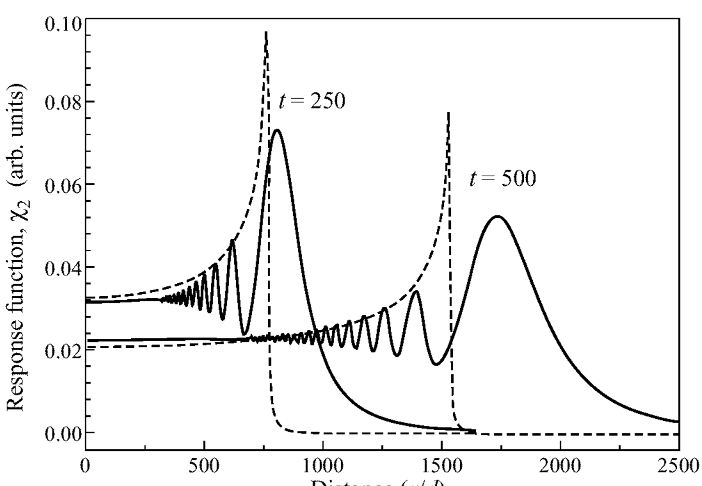

Fig. 1. The envelope of the CDW response function $\chi_2(x,t)$ for two moments of time (t is normalized to d/v_F, d being the wire diameter). Solid lines present the Coulomb interaction case, dashed lines correspond to the short-range interaction with the effective interaction parameter $g_{eff} = 0.326$.

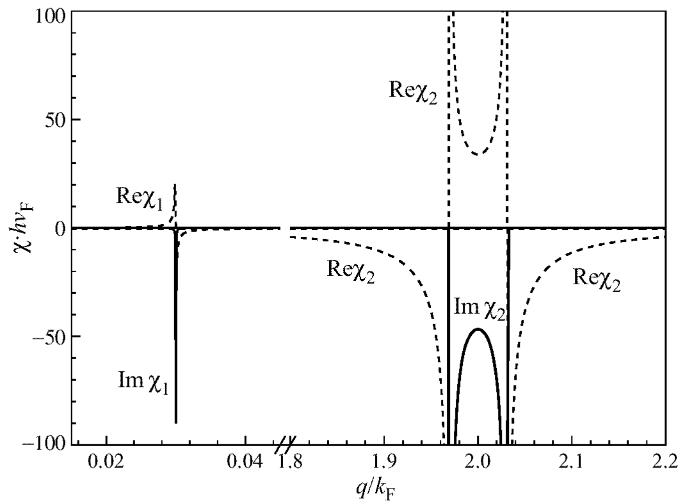

Fig. 2. The real and imaginary parts of the susceptibilities caused by the LW (χ_1) and CDW (χ_2) density components. The calculations are for $g = 0.3$ and $\hbar\omega = 0.1\varepsilon_F$.

The response function $\chi_2(x, t)$ coming from the CDW density describes the density oscillations rapidly varying in space with the wave vector $2k_F$ and modulated by the envelope that has a form of a propagating front. This is illustrated by Fig. 1 where the envelope is shown for two moment of time. The solid lines show the Coulomb interaction case. The dashed lines correspond to the short-range interaction with the effective interaction parameter g. In the latter case the front propagates with the constant velocity $v = v_F/g$ and the amtlitude decreases with the time as t^{-2g}.

The spectrum of the CDW susceptibility $\chi_2(q, \omega)$ is characterized by the presence of a narrow band of strong absorption near $q = 2k_F$. It is shown in Fig. 2. The band edges are determined by the dispersion of bosons in Luttinger liquid, $\omega = \omega(q)$. The edges are positioned at $q = 2k_F \pm q_\omega$ where q_ω is the wave vector of bosons at the frequency ω. The imaginary part of the susceptibility Imχ_2 as a function of q is determined by the electron-electron interaction potential. Im$\chi_2(q, \omega)$ is connected with dynamic correlations of interacting electrons and coincides practically with the dynamic form-factor. In the short-interaction case, $q_\omega = \omega/v$ and the singularities of Imχ_2 at the band edges have the form: $\mathrm{Im}\chi_2 \propto \left|(2k_F \pm \omega/v)^2 - q^2\right|^{(g-1)}$. If electrons interact via the Coulomb law, the correlations are strongly changed [3] which results in corresponding change of the absorption band. The real part of the susceptibility Reχ_2 does not equal to zero in the whole region of q and ω. It has also the singularities at the band edges. In the long-wavelength limit, Reχ varies as Re$\chi \sim q^2$ in the whole frequency range showing that the CDWs do not contribute to the screening.

3. The dissipated power

The imaginary part of the susceptibility determines the conductivity. Since the CDW density contributes significantly to the susceptibility, a strong effect in the conductivity can also be expected. To show this we consider the situation where the 1D conductor without leads is locally disturbed by the electric potential of the conducting probe. The conductivity is determined by the power dissipated in the sample. It consists of two parts P_1 and P_2 that correspond to the LW and CDW components of the electron density. The dissipated

power due to the LW density is estimated as $P_1 \propto (\omega^2/g)|\varphi_{\omega/v}|^2$, where $\varphi_{\omega/v}$ is the Fourier harmonic of the external potential at the wave vector ω/v. The power caused by the CDW density depends much strongly on the interaction potential and on the frequency. Thus, for the short-range interaction

$$P_2 = \frac{e^2}{h} \frac{\Gamma(\frac{1}{2})}{4^g \Gamma(g)\Gamma(g+\frac{1}{2})} \left(\frac{\omega}{v k_F}\right)^{2g} k_F^2 \left|\varphi_{2k_F}\right|^2 . \tag{2}$$

It is of interest that the ratio of the above powers $P_2/P_1 \sim \omega^{2g-2}$ increases when the frequency is decreased. Hence in the low frequency regime, the dissipative conductance is determined mainly by the CDWs rather than the LW density as it is commonly believed.

Acknowledgements

This work was supported by RFBR-Moscow Region grant No 01-02-97017, Program "Physics of solid state nanostructures" grant No 97-1054 and Program "Surface atomic structures" grant No 5.3.99.

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